BOLOMETRIC DETECTORS FOR SPACE ASTROPHYSICS

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ABSTRACT

An overview is given of the status of arrays of bolometric detectors for space astrophysics at wavelengths from ~ 40 to ~ 3000µm. The existing technologies based on semiconductor thermistors that are being prepared for current space missions are described first. The new opportunities provided by superconducting TES technology for large format arrays with multiplexed readouts are then described. Finally, ideas for long wavelength superconducting photon detection are described. References are given to papers on these subjects from the workshop.

INTRODUCTION

Bolometers are thermal detectors which consist of an absorbing element, a resistive thermometer to measure the temperature rise and a weak thermal connection to a heat sink at some low temperature. Bolometers are used as direct detectors from far-infrared to mm wavelengths and as heterodyne mixers [1-3] at submillimeter wavelengths. In this article we focus on direct detection for astronomical applications. Important noise mechanisms in bolometer systems include thermal fluction noise, Johnson noise, excess (low frequency) noise and amplifier noise. As there is no phase conserving amplification involved, direct detectors do not produce quantum noise. Bolometric receivers use cooled optics, baffles and filters to minimize the photons from sources other than the in-band signal from the sky. An important goal of bolometer design is to reduce all other noise sources below the level of the noise from fluctuations in the rate of arrival of signal photons. For far-infrared space missions, with cooled optics, this corresponds to ~ 3×10^{19} $WHz^{-1/2}$ for photometry[4], which can be achieved, and ~ 10^{20} $WHz^{-1/2}$ for spectroscopy[4,5], which is more difficult.

Thermal noise in bolometers decreases with decreasing operating temperature as a power law. The dark current noise in photon detectors, by contrast, decreases exponentially with decreasing temperature. Both bolometers and Ge:Ga photoconductors are used in the 40-200µm range. The photoconductors operate at higher temperatures, and multiplexed 1024 element arrays have been built for SIRTF[6]. However, quantum efficiencies are low, the time response is complicated and calibration is difficult[7-9]. Bolometers have better operating characteristics, but require lower temperatures and multiplexed arrays are only now being developed. Future developments, such as multiplexed arrays of bolometers or multiplexed arrays of long wavelength photon detectors with good operating characteristics [10-15], can be expected to shift the wavelength ranges over which these technologies are used.

Bolometers are used on CMB measurements at wavelengths as long as 3,000µm (90GHz) and antenna-coupled bolometers should perform well at even longer wavelengths. HEMT amplifiers are also used in direct detection systems at these wavelengths. A comparison between the sensitivities of HEMT and bolometer receivers depends on both the correlations in, and the rate of arrival, of the detected photons[4].

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If the photon occupation number is unity, as is the case when observing a black body in the Rayleigh-Jeans limit, then the correlated photon noise is the same as the quantum noise. In practice, the sensitivities of optimized single polarization bolometers and HEMTS are essentially the same for CMB measurements at frequencies up to ~60 GHz[4,17,18]. At frequencies approaching the peak of the black body curve, however, the photon occupation number falls below unity, the photon correlations disappear and the sensitivity of photon noise limited bolometric receivers to small changes in CMB temperature becomes rapidly better than that of quantum noise limited HEMT receivers. Since the sensitivities of both HEMT and bolometric pixels are approaching fundamental limits, future improvements in receiver sensitivity will come from the use of larger arrays.

The radiation absorbing element most often used in bolometers is a thin metallic film with a sheet resistance of 377 ohms per square supported on a membrane of Si or low stress silicon oxy-nitride (LSN) and followed, after a quarter of a wavelength, by a reflecting backshort. This absorber and its support can be lithographed into a square mesh or a radial spider web to reduce the cosmic ray cross-section as long as the average sheet resistance remains the same and the mesh spacing is small compared with the wavelength.

Some instruments use filled arrays of bolometers which fully Nyquist sample the focal plane. Examples include the GSFC pop-up bolometers for SHARC-II[19] and the CEA two-level structures being developed for Hershel/PACS[20,21]. Another approach widely used at the longer wavelengths is a close-packed array of horn (or other) antennas in the focal plane as is typically used with the Caltech/JPL spiderweb bolometers[17]. Horn-coupled arrays can give rapid mapping with relatively few detectors, but produces a sparsely sampled pattern on the sky, so that the array must be dithered or scanned to fill in a map. Corrugated (scalar) horns preserve polarization and the antenna pattern is good enough that they can directly view ambient optics as on Planck/HFI and ACBAR. Smooth walled conical (or Winston) horns are a less expensive choice when polarization is not an issue, but a cold aperture stop is required as on SCUBA, SPIRE, BOOMERANG, MAXIMA and MAXIPOL. The choice between close-packed and horn-coupled architectures depends, among other things, on whether the factor that limits the array size is the available focal plane area or the complexity and power dissipation associated with the number of detectors[22].

Strong interest in measurements of the polarization anisotropy of the CMB is driving the development of polarization sensitive bolometers. Dual polarization bolometers can be made by using two closely spaced orthogonal uni-directional grids, each attached to its own thermistor, rather than a single two dimensional mesh for the absorbing layer. Dual polarization bolometers of this type made by Caltech/JPL[17] will be used for a number of CMB polarization experiments including Planck/HFI, QUEST and BICEP. The frequency-selective bolometers being developed at Chicago/GSFC use several grids in series to obtain several frequency bands and two polarizations in a single multimode pixel. Multimode detectors can be useful if the diffraction limit of the telescope is smaller than required for the science[23].

Another approach to the problem of a dual-polarization pixel is being explored at Berkeley[24] and Caltech/JPL[25]. Rather than using horn antennas, coupling to these bolometers occurs by planar lithographical antennas and superconducting microstrip transmission lines[26]. These lines can branch to form diplexers so that one antenna can feed two or more bolometers, which measure different frequency bands. In essence, the low losses in superconductors are being exploited to use microwave integrated circuit (MIMIC) techniques at higher frequencies. In this implementation, the absorbing element of the bolometer is the resistive termination of the transmission line, which can have dimensions much smaller than the wavelength. This approach is best suited to the superconducting thin film (TES) thermistors which will be described below. Requirements for a high performance CMB polarization system include an antenna pattern narrow enough to couple to the telescope optics, simultaneous measurement of two orthogonal polarizations and simultaneous measurement in several frequency bands. The Berkeley[24] group is making crossed double-slot dipole antennas, coupled to two bolometers. The difference between the outputs of the bolometers is sensitive to the polarization of the mode illuminating the pixel. One Si lens per pixel and a cold aperture stop are used to match the antenna pattern to the telescope beam. The Caltech/JPL[27,28] group is studying an array of many slot antennas to give a narrow antenna pattern which couples directly to the telescope beam. It has a wide frequency bandwidth that can be divided into several photometric bands. Existing designs do not couple simultaneously to two polarizations.

SEMICONDUCTOR THERMISTORS

The classic thermistor technology for bolometers is a heavily doped and compensated semiconductor which conducts by a hopping process that yields a resistivity α $\exp(T/T_0)^{1/2}$. These thermistors are made by ion-implantation in Si, or by neutron transmutations doping (NTD) in Ge. The impedance is selected to a few MΩ to minimize the noise in JFET amplifiers which are operated at ~ 100K. This technology has been carefully optimized for 20 years and is used for all current observations, and most experiments now under construction[19] including the bolometric experiments on Hershel[25] and Plank[17,29]. Limitations to this technology include a small amplifier noise margin and a very difficult thermal mechanical and electrical interface between the bolometers at 100-300mK and the amplifiers at 100K. There are no practical approaches to multiplexing many such bolometers to one JFET amplifier. Current arrays require one amplifier per pixel and are limited to a few hundred pixels. The CSA is developing an array of very high impedance ion-implanted Si bolometers for Hershel/PACS that will use MOS multiplexers and amplifiers[20].

TES BOLOMETERS

The voltage-biased superconducting bolometer with transition edge sensor (TES) and with SQUID readout amplifier is a negative feedback thermal detector with many favorable operating characteristics. It can be made entirely by thin film deposition and optical lithography. The feedback reduces the time constant, improves the linearity, and isolates the bolometer responsivity from changes in infrared loading or heat sink temperature. There is also some suppression of Johnson noise. The SQUID amplifiers operate at bolometer temperatures, dissipate very little power and have significant noise margin. These bolometers are being developed at GSFC/NIST[30-32], Berkeley[24] and Caltech/JPL[25,28] with appropriate architectures for both close packed and antenna-coupled arrays.

At low operating temperatures ≤ 100mK, the small absorbing element of an antenna-coupled bolometer can be combined with the TES and deposited directly on the Si substrate. The weakness of the coupling between electrons and phonons can provide adequate thermal isolation in these hot electron TES bolometers[33] without a membrane suspension.

Large format arrays of TES bolometers require output multiplexing to avoid very large numbers of leads leaving the cryostat. Lines of ~30 detectors can be multiplexed before amplification using superconducting thin film technology. The NIST group has developed a time-domain multiplexer which uses a SQUID for each bolometer to switch the outputs sequentially through a single SQUID amplifier[34]. Groups in Berkeley and Helsinki are developing frequency-domain multiplexers which combine the signals from a row of bolometers, each of which is biased at a different frequency. The signals are then amplified by a single SQUID and recovered with ambient temperature lock-in amplifiers[35,36]. The success of the TES array technology ultimately depends on the success of one or both of these multiplexers.

NOVEL CONCEPTS

The TES bolometer and multiplexer architectures, as well as the SIS and HEB mixers, demonstrate the great flexibility of superconducting technology. There are even more new ideas for superconducting direct detectors. There is work at GSFC on the old dream of a true integrating bolometer in which the thermal conductance can be switched on and off[37]. There is also work on superconducting photon detectors that could operate at higher temperatures than bolometers for the same wavelengths. There are even ideas for a far-infrared superconducting photon counter. In a typical infrared photon detector, the incident photon excites an electron into the (nearly) empty conduction band or out of the (nearly full) valence band of a cold semiconductor. The current due to these carriers is then measured before they recombine. An analogous detector can be made in a superconductor. In this case, the electrons in a cold dark superconductor are bound into Cooper pairs. An incident photon can break a pair and create two single electrons, or quasiparticles. Given a readout scheme that is sensitive to the quasiparticles, but not to the pairs, a superconducting photon detector can be made.

The inductance of a superconducting strip includes a contribution that is proportional to the density of quasiparticles. A detector is being developed at Caltech/JPL[38] that places the inductor in a microwave resonant circuit that is AC biased off resonance, so that the transmitted signal depends on the quasiparticle density. A large number of such detectors can be read out (multiplexed) through a single broadband HEMT amplifier if each one is biased at a different frequency.

In a different development at Yale/GSFC[39], the quasiparticle density is measure with a superconductor/insulator/normal metal tunnel junction that transmits quasiparticles, but not pairs. The tunneling quasiparticles go to the gate of a superconducting single-electron transistor (SET). The gate is so small that a single electron will measurably change the SET current. This device can thus operate as a submillimeter photon counter. Since photon rates at these frequencies are high even from dark regions of the sky, the Yale group is developing a radio frequency SET with a high readout rate which is appropriate for multiplexing the outputs of photon counters for astrophysical measurements.

CONCLUSIONS

Most of the electromagnetic radiation in the universe is radiated from far-infrared to millimeter wavelengths. There is great interest in new mission such as SAFIR and CMBPOL to explore this radiation. These missions will require large format arrays of 10^3-10^4 detectors to meet their objectives. There is no shortage of ideas of how to meet this need with some combination of photon and thermal detectors. However, much work remains to be done before missions can be designed. Since there are no commercial applications, NASA funding of both near term developments such as TES bolometer array systems and farther term developments such as far infrared and millimeter wave photon detector arrays will be essential to carry out the science that is being proposed.

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